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Impact of forest maintenance on water shortages: Hydrologic modeling and effects of climate change

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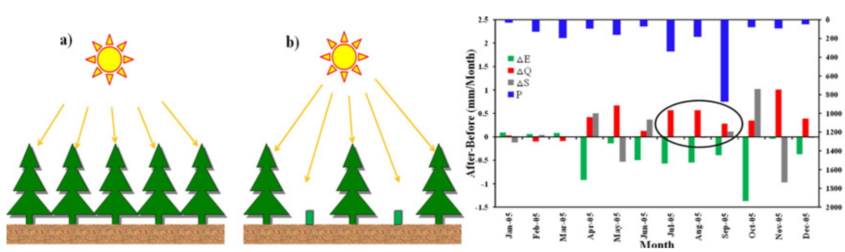
HIGHLIGHTS

- We present a model to explore impact of forest management on hydrologic processes.
- Results indicate that surface flow and soil water increases after forest management.
- Climate change has little impact on near-future discharge, dramatic impact by 2100.
- Climate change leads to reduced soil moisture in the future period.
- Forest hydrology models show potential for informing environmental management.

GRAPHICAL ABSTRACT



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ABSTRACT

The importance of water quantity for domestic and industrial water supply, agriculture, and the economy more broadly has led to the development of many water quantity assessment methods. In this study, surface flow and soil water in the forested upper reaches of the Yoshino River are compared using a distributed hydrological model with Forest Maintenance Module under two scenarios; before and after forest maintenance. We also examine the impact of forest maintenance on these variables during extreme droughts. Results show that surface flow and soil water increased after forest maintenance. In addition, projections of future water resources were estimated using a hydrological model and the output from a 20 km mesh Global Climate Model (GCM20). River discharge for the near-future (2015–2039) is similar to that of the present (1979–2003). Estimated river discharge for the future (2075–2099) was found to be substantially more extreme than in the current period, with 12 m^3/s higher peak discharge in August and 7 m^3/s lower in July compared to the discharges of the present period. Soil water for the future is estimated to be lower than for the present and near future in May. The methods discussed in this study can be applied in other regions and the results help elucidate the impact of forests and climate change on water resources.

1. Introduction

Water is both the foundation of human societies and a major source of vulnerability to extreme events such as droughts and floods. Water

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shortages and droughts are increasing in frequency and intensity as climate change and population growth compound already strained water resource systems (Brekke, 2010). Global climate change is likely to lead to higher evapotranspiration and consequently enhance drought occurrence (Harriet Bigas et al., 2012) as population growth simultaneously increases water demand. Human activities have caused increasing concentrations of atmospheric CO_2 and other gases in the atmosphere which lead to increases in potential evapotranspiration and, as a consequence, surface heating (Trenberth et al., 2014). This may increase actual evapotranspiration which contributes to drought conditions. Both frequency and intensity of drought conditions in many countries appear to be increasing, e.g. Britain in 2012 (Bell et al., 2013), Serbia in 2000 (Gocic and Trajkovic, 2013), South China after 2003 (Zhang et al., 2013), United States in 2011–2012 (Grigg, 2014), European-wide in 2003 (Byzedi et al., 2014), Moscow region in 2010 (Lupo et al., 2014), etc. Droughts affect woody plant mortality (Twidwell et al., 2014), cave species (Shu et al., 2013), plant growth in general (Lipiec et al., 2013), and children's respiratory health (Smith et al., 2014), among many effects. Additionally, severe water shortages will be coincident with increasing water stress with important implications for human health (Oki and Kanae, 2006; Eliasson, 2015) and water pollutions problem (He et al., 2011). Droughts have adverse impacts on water quality with responses in water temperature, eutrophication, major ions and heavy metals (Zwolsman and van Bokhoven, 2007). Forest maintenance studies are essential to reduce drought stress and water shortages, particularly as droughts become increasingly serious and threatening to human societies and the environment.

The effect of forests on hydrology has been explored in numerous studies. Forests can store water during flood events, a function that can be lost when soils are fully saturated during extreme rainfall events (Scherrer et al., 2007). Forests have a significant impact on extreme flows by contolling flood routing (Eisenbies et al., 2007). Soil erosion increases under poor forest management (e.g. clear cutting or over-harvesting) (Grace, 2004). The impact of forest use and reforestation on soil hydraulic conductivity has been studied in the Western Ghats of India (Bonell et al., 2010). Many studies focus on future challenges and directions of forest hydrology. Forest gap models have been applied successfully to simulate tree species composition and have been improved to simulate patterns of aboveground biomass more realistically along drought gradients (Bugmann and Cramer, 1998). The impact of droughts on forest growth at different time scales has been investigated to understand forest response to climate change, and the increasing frequency of droughts (Pasho et al., 2011). Nakai and Kisanuki (2011) investigated tree cutting impact of two specific tree species in the Yoshino River basin. However, the impact of forest maintenance on Japanese river basins remains an important topic, particularly given the implications for water shortages in the context of climate change.

The warming of the climate system has led to changes in climate variables and caused increases of extreme climate conditions, e.g. storms and droughts. Previous researches have focused on drought hydrology and climate change impacts on droughts. The Standard Precipitation Index (SPI) is used for long-term drought forecasting (Belayneh et al., 2014; Raziei et al., 2013), multivariate approaches have been added to the SPI (Bazrafshan et al., 2014), and a Multivariate Standardized Drought Index has been coupled with the Standardized Precipitation Index (SPI) and the Standardized Soil Moisture Index (SSI) (Hao and AghaKouchak, 2013). Burke and Brown (2010) assessed regional drought events in the UK to predict future change due to increases in greenhouse gas concentrations. Recent research has also characterized uncertainty based on the choice of drought index and the internal variability of the Canadian Regional Climate Model driving data (PaiMazumder and Done, 2014). Other modeling studies investigated the combined uncertainties in GCM output, scenarios choice and downscaling method (Raje and Mujumdar, 2010). Stringer et al. (2009) assessed the impact of international and national policies in support of local adaptive strategies in southern Africa on the three interlinked drivers of climate change, desertification and drought. The impacts resulting from land-use and climate change on droughts have been analysed using physically-based models in the Netherlands (Hupsel, Gulp and Noor), Norway (Haugland) and Scotland (Monachyle) (Querner et al., 1997). However, little research has analysed droughts using hydrological models and high resolution GCM data in Japanese river basins.

The main objectives of this study are to analyse the change of surface flow and soil water under extreme droughts before and after forest maintenance, and to project future water resource conditions and soil water concentrations using a distributed hydrological model driven by 20 km mesh high resolution GCM data for Japan. Additionally, we discuss the role of forests and forest maintenance in ameliorating drought severity. Management recommendations are provided for future forest management with consideration to extreme droughts and future climate scenarios.

2. Study site and data collection

2.1. Description of study site

We focus on the upper reaches of the Yoshino River, Kochi Prefecture in the Shikoku Island of Japan. The upper basin of the Yoshino River (Fig. 1) is the upper stream from the Sameura Dam. The Sameura Dam is used for hydropower, flood control, domestic water supply, and irrigation. The Yoshino River is the second longest river on Shikoku Island, spreading over the island's four prefectures (Kamada et al., 1997). The river has a long history of flood control beginning in 1585 during the Edo period.

The basin area of the upper Yoshino River is about 389 km^2. The highest elevation is 1890 m, and the lowest elevation is 313 m. The annual rainfall in the mountainous area of this catchment is 2500 to 3000 mm, and most rainfall is concentrated from July to September (Jaranilla-Sanchez et al., 2012). Extreme historical discharge from the Sameura Dam is 0 m^3/s during the dry season (October to February) and 4000 m^3/s during the wet season (July to September) (KPPDWRPD, 2011). In recent decades, water shortages became serious in the Yoshino river basin (Nyunt et al., 2014). Most serious water shortage after the construction of Sameura Dam happened in 2008 (Luo et al., 2011). Water storage in the Sameura Dam approached zero on August 31, 2008. After the construction of Sameura Dam the water use capacity of this dam is close to zero which sometimes continues for 20 days. From the 1960s to the 1970s, deforested areas of the Yoshino River were reforested. Reforested areas in the Yoshino River basin matured during the 1980s and 1990s. Ten parameters have been used in the SWAT model for this drought study. The detail description of those ten parameters is presented in Table S1.

2.2. SWAT model inputs

2.2.1. Digital elevation model (DEM)

The digital elevation model (DEM) came from published data of the Japanese Ministry of Land, Infrastructure, Transport and Tourism (MLIT). The original DEM was transferred into point shape files using ArcGIS9.3 Japanese version. The original DEM is 50 m mesh resolution. Original 50 m mesh DEM data was scaled into raster files at 100 m mesh. The DEM (Fig. 1) is used to delineate the watershed boundary, river channel network, flow direction, flow accumulation and subbasins.

2.2.2. Soil type

Soil type data was downloaded from the land and classification survey at the website of Land and real property in Japan, Japanese Ministry of Land, Infrastructure, Transport and Tourism (MLIT). Soil type data is 1:200,000 seamless. The original soil type data was converted into 100 m mesh raster file. The main classifications of soil type include

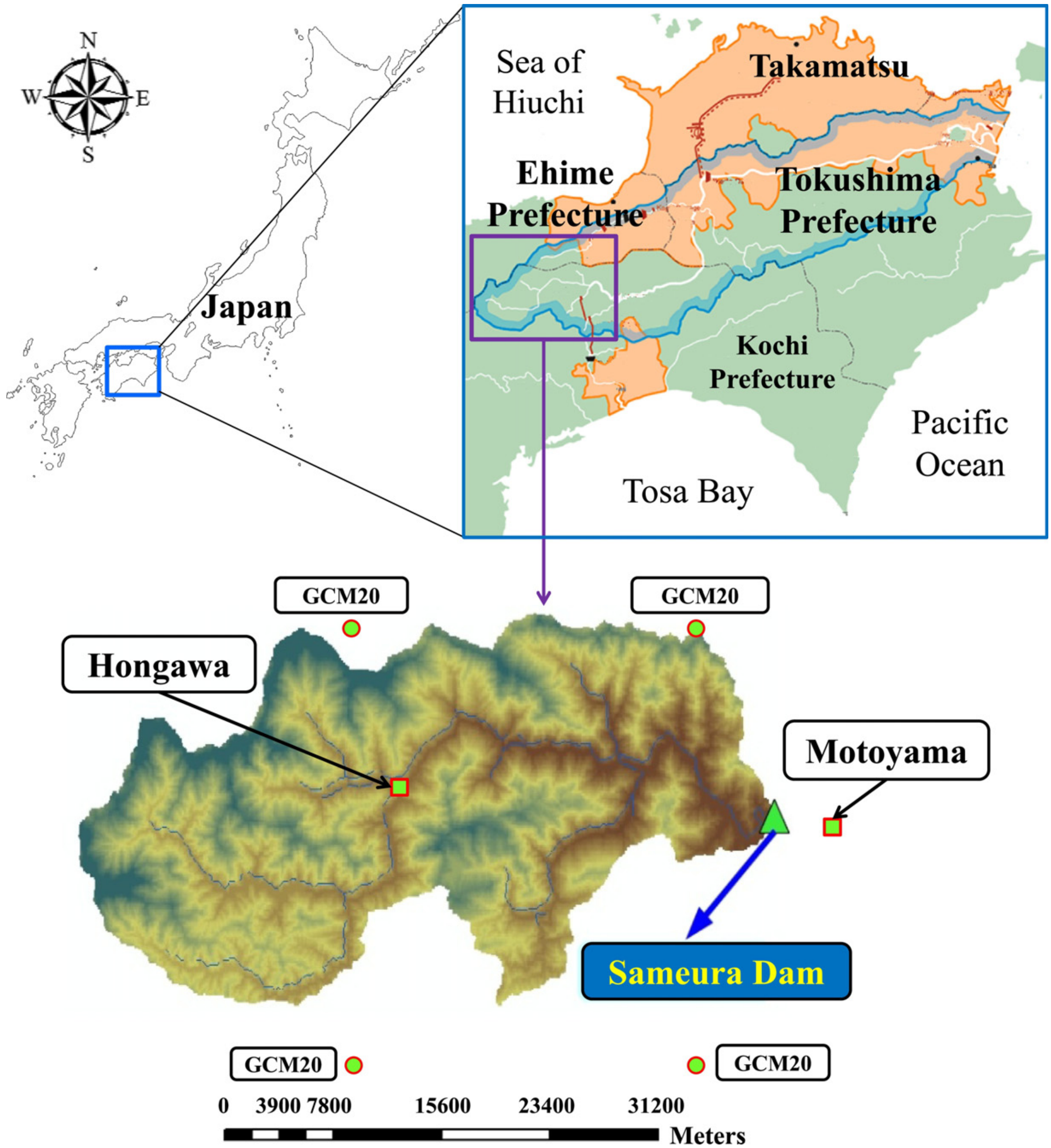

Fig. 1. Boundary, river channel and digital elevation model (DEM) information of the Yoshino River upper stream.

Brown Forest Soils (Cambisols), Red and Yellow Soils (Acrisols and Luvisols) and Ando soils (Andosols). The Brown Forest Soils represent 97.74%, the Red and Yellow Soils 0.1%, and the Ando soils 2.16% in the study area.

2.2.3. Land use

The original land use data was downloaded from the website of the National Land Numerical Information download service, National Information Division, National and Regional Policy Bureau, MILT of Japan. The original land use data has been converted into polygon shape file using the KSJ Designated Regional area data creation tool. The polygon shape file of land use data was converted to 100 m mesh raster file in ArcGIS9.3. Forest coverage is ~88%, agricultural land is only 1.5% and urban areas account for ~0.1% of this catchment.

2.2.4. Hydro-meteorology data and water supply data

The daily observed rainfall, temperature and wind speed data at the Motoyama and Hongawa Automated Meteorological Data Acquisition System (AmeDAS) stations from 1979 to 2008 was obtained from Japan Meteorological Agency (JMA). The solar radiation and humidity data (2003–2008) were taken at the Kochi observation station, JMA. The observed discharge data (1980–2008) is taken as the inflow discharge of the Sameura dam.

This study employs the output from the super-high-resolution (20 km mesh horizontal resolution) Global Climate Model (GCM20), developed by the Japanese Meteorological Research Institute (MRI) (Kitoh et al., 2009) as the predictor. As shown in Fig. 1, four points of GCM20 cells are identified in the Yoshino River basin. Precipitation and temperature data were downscaled from the SDSM model and the GCM20 cells and used as the input to the SWAT model. The

downscaled results were validated using the observed meteorological dataset including temperature and precipitation, which can be obtained through the AmeDAS database from the Japan Ministry of Land, Infrastructure, Transport and Tourism (MLIT). Simulated river discharge from the SWAT model was also validated by comparison to observed river discharge data from MLIT. The Setogawa water intake weir located in the upper stream of the study site was also considered in the SWAT model. The average daily water intake data for each month was input into the NO.18 sub-basin in the SWAT model.

3. Methods

3.1. Forest maintenance module

Periodic tree thinning involves cutting trees at regular intervals and managing forests to support sustainable wood production with important implications for hydrology. Forests without maintenance are illustrated in Fig. 2(a). In Fig. 2(b), it shows forest management by thinning, with interior tree removal between adjacent rows of trees. After forest maintenance, the leaf area index (LAI) increases, evapotranspiration of the forest area decreases, and soil water increases. Forests managed with periodic tree thinning have lower evapotranspiration after forest maintenance than pre-forest maintenance. Grass growth increases in the case after forest maintenance, and precipitation in the post forest maintenance case reaches the ground unimpeded, and water more easily infiltrates into the soil.

The analysis of discharge and underground water storage before and after forest maintenance required changing three key parameters, saturated hydraulic conductivity (SOL_K.sol), leaf area index (LAI) and available water capacity (SOL_AWC.sol) in the calibrated SWAT model (Table 1). The forest area of our study catchment is managed by the Reihoku Forest Office, Shikoku Regional Forest Office (RFO, 2014). The average planted forest area is 17,076 m^2 which is 62.7% of the total forest area of 27,238 m^2, and the average natural forest area is 10,162 m^2 which is 37.3% of the total forest area (RFO, 2014). The infiltration capacity of the planted forest is ~1/3 that of the natural forest (YRBV21C, 2004). Ogawa et al. (2003) reported that the saturated hydraulic conductivity (SOL_K.sol) of planted forests is 360 mm/h and that of natural forests is 900 mm/h. The saturated hydraulic conductivity (SOL_K.sol) before forest management in our study catchment is calculated as below:

$$\text{SOL\_K.sol (be)} = 360 * 62.7\% + 37.3\% * 900 = 561.42 \text{ mm/h}$$

The leaf area index (LAI) of different forest types is based on the previous study of Ishii et al. (1999). A detailed description of LAI in different forest types is shown in Table S2. The LAI in this study is calculated as the LAI before forest management and LAI after forest management based on the values from Table S2.

Table 1
Values of parameters in the periods before and after forest maintenance.

Parameters	Unit	Before forest maintenance	After forest maintenance
SOL_K.sol	mm/h	900	561.42
LAI	m^2/m^2	6.25	5.12
SOL_AWC.sol	mm/mm	0.4739	0.4881

$$\text{LAI (Before forest process)} = (6 * 17076 + 8 * 10162 * 1/3 + 6 * 10162 * 2/3)/27,238 = 6.25$$

$$\text{LAI (After forest process)} = (4.2 * 17076 + 8 * 10162 * 1/3 + 6 * 10162 * 2/3)/27,238 = 5.12$$

Shinomiya (2007) reported that the soil water content with a tree thinning rate of 33% is 3% higher than that without tree thinning. Available water capacity (SOL_AWC.sol) without tree thinning ranges from 0.3 to 0.6. The available water capacity (SOL_AWC.sol) with tree thinning is calculated by adjusting the value of SOL_AWC.sol from the calibration parameter of SWAT-CUP. A typical tree thinning rate is 30%.

The detailed research process is described as follows (Fig. 3):

(1) Set up the SWAT model with input data including DEM, land use, soil type, observed rainfall, and observed discharge. Run the SWAT model. The default values of the 10 parameters (for detailed description see Table S1) are obtained. After successfully running the SWAT model, a TXTINOUT document with information about input data and output format in SWAT is created.
(2) The TXTINOUT document is input into the SWAT-CUP model to calibrate the model with the observed discharge. The best parameters are obtained from SWAT-CUP based on the best calibration result.
(3) The parameters SOL_K.sol, LAI and SOL_AWC.sol are set up before forest maintenance in SWAT-CUP (see Table 1). The simulation results of discharge and underground water storage before forest maintenance are obtained from SWAT-CUP.
(4) These three parameters are reset for the period after forest maintenance and given to the SWAT model (see Table 1). The simulation results for discharge and underground water storage after forest maintenance are obtained from the SWAT model.

3.2. SWAT model

The SWAT model is a physics-based, long-term, distributed hydrologic model (Arnold et al., 1998). Many applications of the SWAT model have

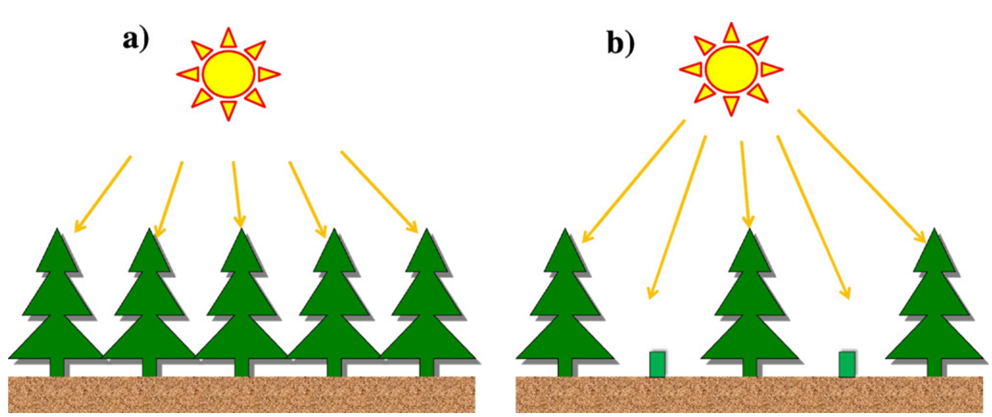

Fig. 2. Schematic figure of forest maintenance using tree thinning: a) Before forest maintenance, b) After forest maintenance.

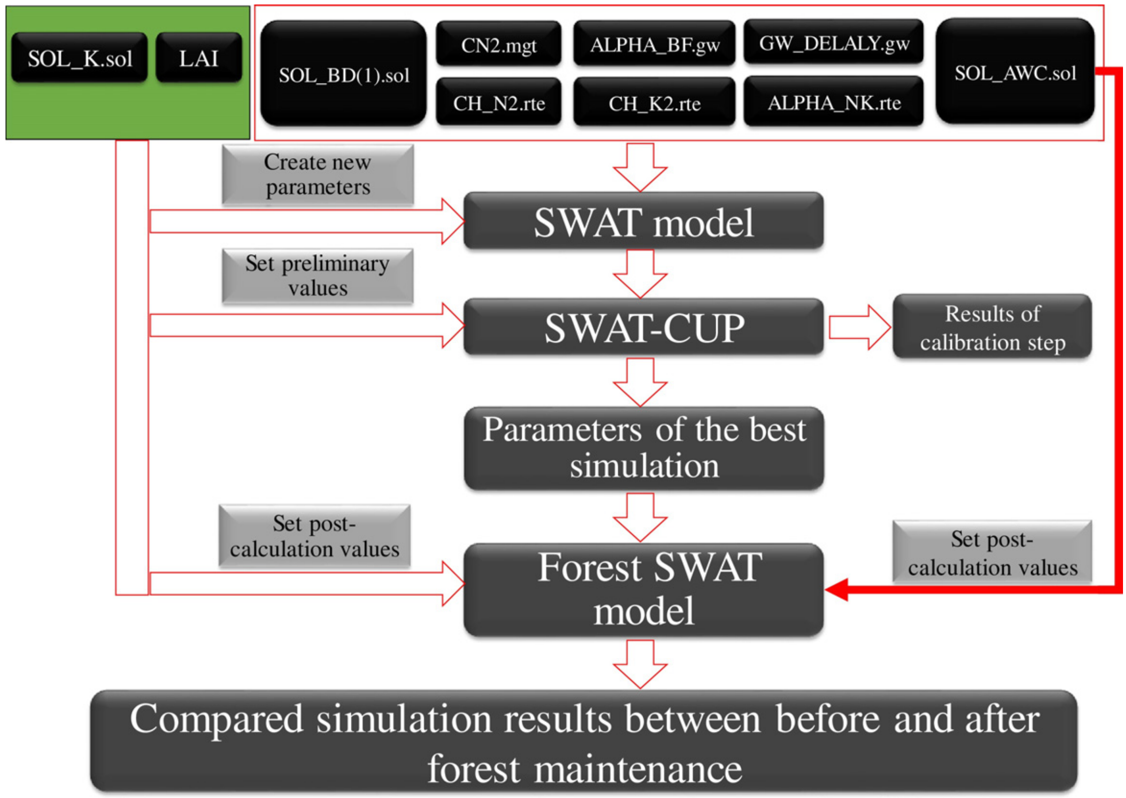

Fig. 3. Framework of the analysis processes (The post-calculation value for SOL_K.sol, LAI and SOL_AWC.sol is in Table 1.)

been driven by the needs of various government agencies, particularly in the U.S. (CEAP, 2008; Gassman et al., 2007) and the European Union, which require direct assessments of land-use and climate change, and other factors in a broad range of study sites for various applications. Several successful applications have been reported for studying the impact of climate change on water resources in India (Leichenko, 1993), assessing runoff and snow melt issues in the Yellow River of China (Zhang et al., 2008), and assessing water availability in Africa (Schuol et al., 2008). The SWAT model is continuously developed and refined by the U.S. Department of Agriculture (USDA) – Agricultural Research Service (ARS) and scientists at universities and research agencies around the world. It is a long-term, continuous simulation watershed model designed to evaluate the impacts of management conditions on water yield, sediment yield, and non-point source loadings in the watershed which is divided into several sub-basins called hydrologic response units (HRUs). All the input data, including land use maps, soil maps, DEM and so on overlap in order to produce HRUs, and each HRU is assumed to be spatially uniform.

The SWAT model uses the SCS curve number procedure when daily precipitation data is used while the Green-Ampt infiltration method is chosen when sub-daily data is used to estimate surface runoff. The SCS curve number is defined by Eq. 1.

$$Q_{surf} = \frac{(F_{day} - 0.2Y)^2}{(F_{day} + 0.8Y)} \tag{1}$$

where Q_{surf} is the accumulated runoff or rainfall excess (mm); F_{day} is the rainfall depth for the day (mm); and Y is the retention parameter (mm). The retention parameter varies spatially due to changes in soil, land use, management, and slope and temporally due to changes in soil water content. The retention parameter is calculated by the following Eq. 2.

$$\mathrm{Y} = 25.4\left(\frac{100}{CN} - 10\right) \tag{2}$$

The SCS curve number is a function of the soil's permeability, land use and antecedent soil water conditions. SCS defines three antecedent moisture conditions: 1st – dry (wilting point), 2nd – average moisture, and 3rd – wet (field capacity).

The moisture condition 1st curve number is the lowest value that the daily curve number can assume in dry conditions. The curve numbers for moisture conditions 2 and 3 are calculated from Eqs. 3 and 4.

$$CN_1 = CN_2 - \frac{20^*(100 - CN_2)}{\left(100 - CN_2 + e^{2.533 - 0.0636*(100 - CN_2)}\right)} \tag{3}$$

$$CN_3 = CN_2{}^* e^{0.00673*(100 - CN_2)} \tag{4}$$

In which CN_1 is the 1st moisture condition curve number, CN_2 is the 2nd moisture condition curve number, and CN_3 is the 3rd moisture condition curve number.

3.3. SWAT-CUP

Although SWAT has been applied widely for managing flood events and water resources, calibration and uncertainty analysis is complex with limitations related to input data, complexity of hydrologic process modeling, and uncertainty in physical characteristics (i.e. slope, elevation, soil type, land cover and so on) of a river catchment. Overestimation of uncertainty can result in over-design of mitigation measures, while underestimation of uncertainty can lead to inadequate preparation for potential futures. Fine calibration and uncertainty analysis is required for the successful application of SWAT (Duan et al., 1992; Vrugt et al., 2003). In this study, SWAT-CUP (Calibration and Uncertainty Procedures) is used for integrating various calibration and uncertainty analysis modules into the SWAT model. This program includes five methods including Sequential Uncertainty Fitting (SUFI-2) (Abbaspour et al., 2004; Abbaspour et al., 2007), Generalized Likelihood Uncertainty Estimation (GLUE) (Beven and Binley, 1992), Parameter Solution (Van

Griensven et al., 2006, 2008), Mark chain Monte Carlo (Kuczera and Parent, 1998), and Particle Swarm Optimization for calibration and uncertainty analysis. SUFI-2 is the algorithm for calibration of SWAT. GLUE is a common method for global sensitivity analysis. Generally, GLUE and SUFI-2 provide the widest intervals of the parameter uncertainty among the five approaches. We selected GLUE for calibration and validation in this study, based on the results of the Mean Squared Error (R2) and Nash-Sutcliff (NS) for the model calibration and validation, and the performance of the peak discharge and base flow.

GLUE is an uncertainty analysis technique inspired by Bayesian estimation and propagation of uncertainty. The likelihood measure is associated with a parameter set and reflects all sources of error and any effects of the covariation of parameter values on model performance implicitly. Parameter uncertainty therefore accounts for all sources of error (i.e., input, model structure, parameter and response) (Beven and Freer, 2001). Parameter uncertainty incorporates the likelihood weights of the behavioural parameter set. The likelihood weight of each behavioural parameter set is calculated according to Eq. 1:

$$w_i = \frac{L(\theta_i)}{\sum_{k=1}^{n} L(\theta_k)} \tag{5}$$

where $L(\theta)$ is a large number of parameter sets which are randomly sampled from the prior distribution and each parameter set. The number of behavioural parameter sets is denoted by *n*.

The coefficient objectives of R^2 and NS are used to reflect uncertainty measures and the 95% prediction uncertainty (95PPU) between the 2.5th and 97.5th percentiles. The most frequently used likelihood measure for GLUE is the Nash-Sutcliffe coefficient (NSE):

$$\mathrm{NSE} = 1 - \frac{\sum_{t_i}^{n}\left(y_{t_i}^{M}(\theta) - y_{t_i}\right)^2}{\sum_{t_i}^{n}\left(y_{t_i} - \bar{y}\right)^2} \tag{6}$$

where n is the number of the observed data points, and y_{t_i} and $y_{t_i}{}^{M}(\theta)$ represent the observation and model simulation with parameters θ at time t_i, respectively, and $\bar{y}$ is the average value of the observations.

3.4. Statistical downscaling model

Since Global Climate Model (GCM) output has large-scale spatial resolution, a variety of different methods have been proposed for downscaling large-scale GCM output to the temporal and spatial scales required for climate impact studies in basin-scale research. In this study, a Statistical Downscaling Model (SDSM) was used to downscale the GCM climate data. SDSM is a multiple regression-based tool for generating regional scale future climate scenarios with the ability to capture inter-annual variability better than other statistical downscaling approaches (e.g. weather generators, weather typing) (Wilby et al., 1998, 1999). SDSM combines a stochastic weather generator and a transfer function model (Wilby et al., 2002, 2004) and needs two types of daily input data. The first type corresponds to local endpoints of interest (e.g. temperature, precipitation) and the second type corresponds to the data of large-scale predictors (GCM) of a grid cell closest to the study area. Correlation and partial correlation analysis are performed in SDSM between the endpoint of interest and predictors to select a set of predictors most relevant for the site in question (Wilby et al., 1999; Wilby and Dawson, 2007). A detailed description and application of SDSM in the river basins of Japan can be found in He et al. (2010).

4. Analysis and results

4.1. Calibration and validation results

Based on sensitivity analysis for the discharge calibration performed using SWAT-CUP, SWAT was calibrated and validated for 10 parameters including initial SCS runoff curve number (CN2), base-flow alpha factor (ALPHA_BF), groundwater delay time (GW_DELAY), Manning's "n" value for the main channel (CH_N2), effective hydraulic conductivity in main channel alluvium (CH_K2), base-flow alpha factor for bank storage (ALPHA_BNK), available water capacity of the soil layer (SOL_AWC), saturated hydraulic conductivity (SOL_K), moist bulk density (SOL_BD), and snowfall temperature (SFTMP) (Table 2).

The SWAT model was applied to the upper Yoshino river basin and calibrated using data from 2003 to 2005 and validated using data from 2006 to 2008. The same parameter sets have been used for the daily and monthly simulation. The result of the daily calibration shows that although some peak discharges are lower than the observed discharge, the simulation result of the base flow brackets observed data well with an R^2 of 0.86 (Fig. S2). The result of the daily validation shows that although some peak discharges are under-estimated, the simulation result of the base flow matches the observed data well with an R^2 of 0.79 (Fig. S3).

4.2. Comparing the periods before and after forest maintenance

We focused on one drought event which occurred from July 12 to August 20, 2005 (KPPDWRPD, 2011). Measured daily precipitation was used in combination with daily evapotranspiration and discharge calculated by the SWAT model. The change in soil water between the periods before and after the rain event was calculated using the following equation:

$$\mathrm{P} - E - \mathrm{Q} = \triangle \mathrm{S} \tag{7}$$

Where, P is precipitation, E is evapotranspiration, Q is discharge, and △S is the change in soil water content between periods before and after the rain event.

Change in monthly evapotranspiration (△E), monthly discharge (△Q), and monthly soil water content (△S) are presented in Fig. 4. Drought events have historically occurred from June to September (KPPDWRPD, 2011). Fig. 4 shows that the discharge for the case after forest maintenance increased about 0.6 mm/month in July and August, and the evapotranspiration for the case after forest maintenance decreased about 0.5 mm/month when compared to the case before forest maintenance.

The daily change in soil water is compared between the cases before and after forest maintenance during the drought event in 2005. Fig. S1 presents the increasing trend of soil water dramatically during drought periods from July 12 to August 20, 2005. Fig. 5 shows a comparison of output of seven hydrologic variables from the SWAT model before and after forest maintenance. Detailed description of the seven output hydrological variables is presented in Table S3. The surface runoff contribution to stream flow during time step (SURQ) and water yield (WYLD) increased 1.7 mm and 1.4 mm, and the Lateral flow contribution to streamflow (LATQ) and Actual Evapotranspiration from HRU (ET) decreased 0.4 mm and 1.5 mm for the case after forest maintenance compared to the case before forest maintenance in Fig. 5. By comparison of hydrologic variables, the total loss after forest maintenance is less than that before forest maintenance, and ET after forest

Table 2
Parameters of the best calibration result.

Parameters	Range	Best value
SOL_AWC(1).sol(mm/mm)	0.4–0.6	0.4739
CN2.mgt (−)	20–90	20.875
ALPHA_BF.gw(days)	0–1	0.8285
GW_DELAY.gw(days)	0–500	291.25
CH_N2.rte(−)	0–0.3	0.20625
CH_K2.rte(mm/h)	0–150	149.175
ALPHA_BNK.rte (days)	0–1	0.5315
SOL_BD(1).sol(mg/m³)	1.1–2.5	1.3289

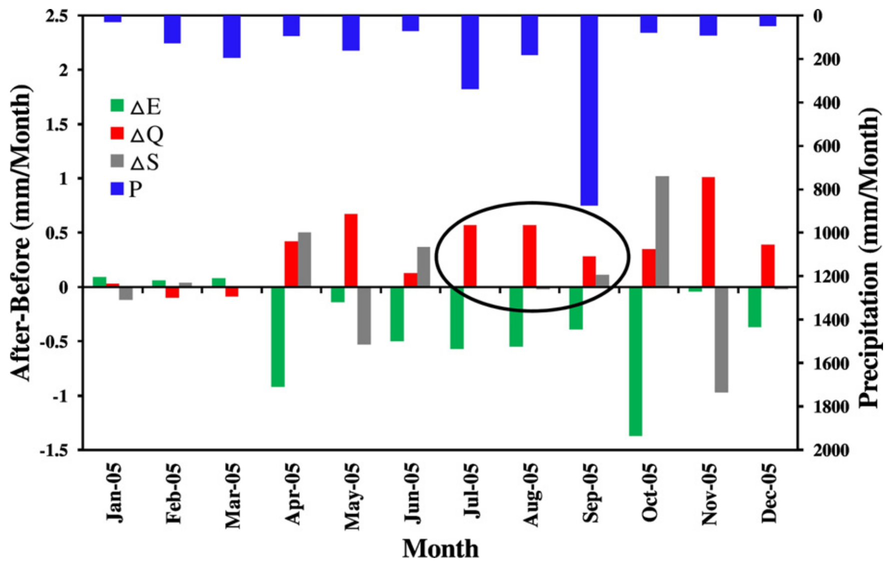

Fig. 4. Monthly hydrological changes in 2005 comparison under the cases of after and before the forest maintenance.

maintenance is significantly less than that before forest maintenance. Based on simulation results, the water yield increased significantly after forest maintenance compared to before forest maintenance during the drought period. Forest maintenance is one of the methods to temporarily release water stress during drought periods.

4.3. Future water condition using downscaled GCM20 data

The results of the average monthly discharge and soil water are presented in Figs. 6 and Fig. S4. The average monthly discharge using GCM20 data for the present period (1979–2003) overestimates observed average monthly discharge due to over-estimation of precipitation from the GCM20 compared with the observed rainfall. However, the trend of the simulation results for the average monthly discharge under the GCM20 data of the present period (1979–2003) is quite like the observed discharge. The simulation results for the average monthly discharge under the GCM20 data of the near future period (2015–2039) are not very similar to the simulation results of the average monthly discharge under the GCM20 data for the present period (1979–2003). The simulation results for the average monthly discharge under the GCM20 data for the near future period (2015–2039) are a little higher in August but a little lower in July than the simulation results of the average monthly discharge under the GCM20 data of the present period (1979–2003). Fig. S4 shows that the monthly soil water content under the near future period (2015–2039) and the future period (2075–2099) is lower in May, but higher in August and October than the monthly soil water content under the present period (1979–2003).

5. Discussion

5.1. Forest maintenance impacts on hydrological runoff and soil water content

Forest maintenance may decrease evaporation and increase soil water during drought periods. It could increase the runoff in the river from our study. The monthly increase in runoff due to tree thinning over the drought period of July and August 2005 is 0.7 mm. Runoff and soil erosion from managed forest areas and harvest plots were found to be higher than from unmanaged forest areas (Hartanto et al., 2003). Canopy cover, sapling density, litter depth and woody debris are considered important factors which impact runoff and soil loss. The decrease of the total basal area in forests resulted in increased total stream-flow, direct runoff, and ground-water recharge by thinning or clear-cut methods (Bent, 2001). The results also identified that sapling density, litter depth and woody debris are the driving factors behind changes in runoff and soil water concentration. Tree thinning that optimizes sapling density could be used to increase runoff during drought periods. Each 10% increase in harvest of forest area resulted in an annual increase in runoff of approximately 28 mm (Eisenbies et al.,

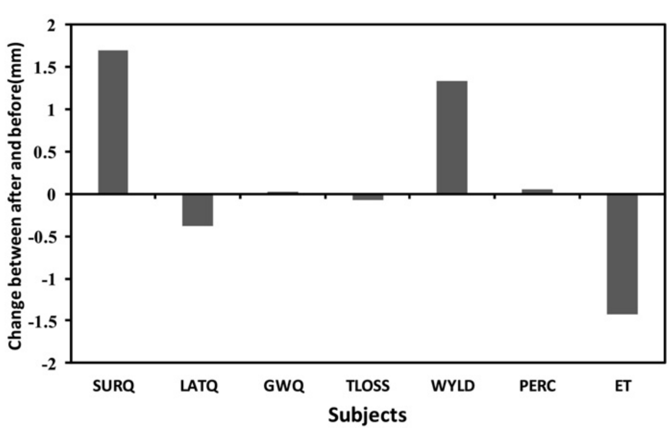

Fig. 5. Comparison of output of seven hydrologic variables before and after forest maintenance.

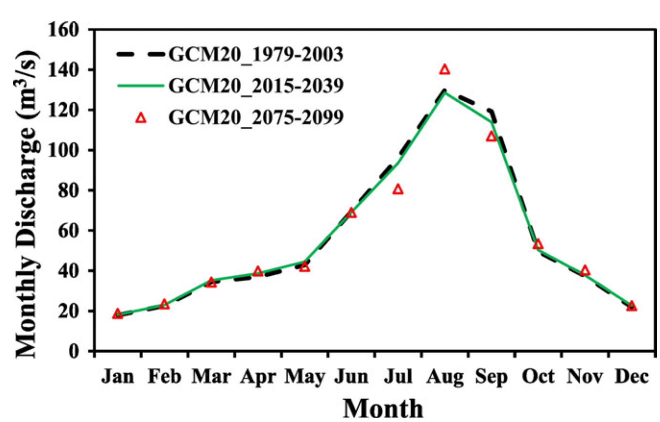

Fig. 6. Results of the monthly discharge under the present period (1979–2003), the near future period (2015–2039) and the future period (2075–2099).

2007). However, the tree thinning may cause the high soil erosion during the flood events which increase the flood risk (Luo et al., 2014 and 2015).

Forest management has important implications for water resources management under climate change. Forest management can increase the total stream-flow and groundwater recharge, leading to greater water supply during drought periods. However, Dijk et al. (2009) showed that forest areas will reduce flood risk during extreme rainfall, and Takara et al. (2004) reported that forests usually maintain high infiltration rates and soil water storage capacity which reduces river flow in the early part of the rainy season before the landscape becomes saturated. However, the effect of forest management became smaller for larger and longer storms (Harr et al., 1975). Two experimental catchments with different forest cover showed higher direct runoff and base flow with the lower momentary discharge located at larger catchments with less vegetation (Iroumé et al., 2005). The effects of forest changes on hydrology in a large catchment showed that historic forest harvesting caused significant increases in water yield (Cui et al., 2012). The results of this study also show that forest management by tree thinning increases surface flow during drought periods. Appropriate forest management is suggested for future water resources management to mitigate the effects of droughts and climate change. Future study will focus on how forest management by tree thing could contribute to increasing flow under a non-stationary climate.

5.2. Interaction between climate change and forest and enlightenments for future forest management

Understanding the effect of future climate change and climate variability on runoff and soil water is an extremely important issue in the context of sustainable water resource management. GCM output has been used for studying the relationship between climate change and forests. The monthly average discharge in August in the future period (2075–2099) is significantly higher than that of the near future period (2015–2039) and that of the present period. However, the monthly average discharge in July of the future period is lower than that of the near future and present period. The detailed spatial runoff analysis of climate change is necessary for understanding the relationship between climate change and forests. Spatial runoff changes associated with climate change are different from nature runoff variability, and runoff anomalies are related to climate variability along north to south gradients (Hulme et al., 1999; Lyu et al., 2015). Increasing surface temperature and sensible heat flux may increase evaporation form forests and lead to drier conditions (Bonan, 2008). Forest thinning may be less sensitive to climate change in some natural forests and harvested wood may be used for biofuels and meeting the need for firewood and building materials (Fenning et al., 2008). Forest management by thinning may increase soil water concentration and can increase runoff. As timber harvesting contributes to both forest services and forest degradation (Yao et al., 2016), maintaining balance between forest restoration and harvesting could lead to long-term benefits for forest ecosystems (Yao et al., 2016). Moderate carbon-market financing offers the opportunity to help the global adoption of sustainable forestry practices while mitigating carbon emissions (Gullison et al., 2007). Effective policies are necessary to ensure the proper management of forests and the reduction in destructive resource extraction. The limitations of this study are the accuracy of GCM output, lack of field operation, and structure of hydrological model. Future work should investigate the impact of forest maintenance on water discharge under various GM scenarios.

6. Conclusion

We investigate 1) hydrologic changes due to forest maintenance and 2) future water conditions using GCM output. Monthly discharge increases substantially in forests that are properly maintained by thinning, even during drought season. The daily soil water content under the case after forest maintenance during extreme drought periods increased much more than in the case before forest maintenance. Post forest maintenance increases in river discharge during periods of drought suggests that proactive management can help alleviate water-shortages during extreme events. This assessment shows that management of forest cover as well as groundwater resources offer opportunities to reduce societal stress associated with droughts. Tree thinning is one promising management technique for enhancing river discharge and water supply. Despite uncertainties, projected future conditions provide a roadmap for managers and policy-makers to identify and implement sustainable solutions to society's problems, particularly within the context of a changing climate.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at http://dx.doi.org/10.1016/j.scitotenv.2017.09.044.

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